SURFACE-IRRIGATION EVALUATION MODELS: APPLICATION TO LEVEL BASINS IN EGYPT

T. S. Strelkoff, A. J. Clemmens, M. El-Ansary, M. Awad

ABSTRACT. *Models for simulating flow in surface irrigation are helpful in evaluating irrigation performance, both as observed in a given field, and in hypothetical, what-if scenarios. However, the use of surface-irrigation simulation and design software is often hindered by the lack of appropriate field values for the infiltration and roughness parameters required as input. Moreover, in various places around the globe, for example, Egypt, as a consequence of local soils and cropping and cultural practices, the field conditions encountered can be quite different from those common in the U.S. Interactive field-parameter-evaluation software, EVALUE, was developed as an aid for estimating these parameters from extensive field measurements. In the interactive process, the engineer-user is provided with information to assist in making his/her choices, but retains full control over the selection of parameter values in the empirical formulas used to describe infiltration and roughness. Parameter estimates made in Egypt were validated by entry into the general surface-irrigation simulation program, SRFR, and subsequent comparison of the predicted and measured results. The procedure verifies both the parameter-estimation techniques and the simulation program. The techniques and models described are presented in terms of Egyptian data, but are sufficiently general to be applicable anywhere.*
Keywords. *Irrigation, Surface irrigation, Simulation, Evaluation, Modeling, Parameter estimation, Infiltration parameters, Roughness coefficients, Arid climates, Egypt.*

Surface irrigation is currently practiced on about 90% of the irrigated land in Egypt, generally at low levels of performance (e.g., poor application efficiencies). Improper on-farm irrigation practices lead to poor water distribution, non-uniform crop growth, excessive leaching in some areas (leading to water logging), and insufficient leaching in others (leading to soil salinity buildup), all of which decrease the yield per unit of land area and per unit of water applied. Improvement in irrigation practices leads to more uniform water distribution, soil and water conservation (sustainability), and economic viability of irrigated agriculture. Thus, efficient on-farm irrigation methods are necessary for increasing crop production per unit of water applied.

In developed countries and in the new irrigated lands in Egypt, significant progress is being made in adopting modern pressurized irrigation systems. Where crop values are high, such capital investment can often be easily justified. However, for lower value crops (per unit of land area) and where such technology is not easy to adopt (e.g., due to infrastructure limitations), surface irrigation is likely to be practiced on a significant portion of irrigated lands for the foreseeable future. Fortunately, under many conditions, modern surface-irrigation methods and practices can achieve significantly higher performance levels than existing methods and practices. To achieve these potential performance improvements in Egypt, substantial effort needs to be directed toward the development and adoption of appropriate technology.

In Egypt, the traditional irrigation method is to break a long field into small blocks (e.g., 5 m × 5 m) and to irrigate each small block independently. The blocks are separated by small dikes, with small channels supplying water to each block. The net result is poor water distribution over the field and land taken out of production. A research project was initiated in 1993 to determine the feasibility of converting irrigation of these small blocks to irrigation of long furrows, border strips, and basins, as practiced in more developed countries. The imprecise leveling of land in Egypt was found to be a significant barrier to adopting this technology. With laser land-leveling growing in popularity in Egypt, this barrier is slowly being removed. However, guidance concerning irrigation and cultural practices is needed to make the conversion successful. An important step in developing this guidance is to define the conditions for infiltration and roughness likely to be experienced, and the effect of cultural practices on them. This article presents one aspect of this larger study.

SOIL AND CROP PARAMETERS IN SURFACE IRRIGATION

Of the conditions that influence surface irrigation performance, infiltration and roughness are the two most difficult to quantify. Infiltration can vary during the growing season in response to changes in soil moisture, compaction, and tillage. Infiltration also varies with soil texture (e.g., from field to field), and may vary within a single field, due to spatial variations in soil properties. Resistance to flow, or roughness, varies over the season,

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with tillage practices and the stage of plant growth. These variations in infiltration and roughness do have an effect on the performance of the irrigation system. Surface irrigation performance in a given field cannot be understood without a determination of the prevailing infiltration and roughness. And before design and management criteria can be developed, formulas for describing infiltration and roughness must be selected and the parameters in those formulas determined. Once these field conditions are defined, a computer program which describes the flow of water over a surface irrigated field (e.g., SRFR, Strelkoff et al., 1998) can be used to develop design and operating criteria.

Prior to this project, little good field data existed on Egyptian cracking clay soils. It proved necessary to make detailed observations of irrigation events with attendant hydraulic behavior, in order to be able to provide simulation models with real input data reflecting Egyptian conditions. Thus, for the purpose of validating the SRFR model under Egyptian conditions, and for establishing the actual infiltration and roughness for a number of field scenarios, a program of field tests (instrumented irrigations) and evaluations was undertaken. This article documents (1) several such test irrigations performed to evaluate field geometry and conditions, (2) a computer program, EVALUE, for estimating infiltration and roughness parameters from the field data, and (3) the results of subsequent simulations of the same irrigations with the computer model, SRFR. In each case, the geometrical configuration consisted of a nominally level basin, in some cases furrowed, and in some, flat planted. In every case, there was no runoff.

Background

In surface irrigation, the factors influencing performance are numerous. Field length, width, furrow cross-section shape, and bottom topography define the geometry. Soil infiltration (e.g., Kostiakov k, *a*, eq. 1) and surface roughness (e.g., Manning n, eq. 6) parameters define the soil and crop hydraulic conditions. The inflow hydrograph defines management input. Each variable has its independent effect and wide practical range. The only feasible way to study the combined influence of some of these variables, or indeed all of them at the same time, is through simulation models.

A variety of methods is available in the literature for estimating infiltration and roughness parameters. The method chosen depends upon the purpose of estimation, the allowable errors, and the soil and crop conditions. Simple procedures are available for routine irrigation system evaluations, but can be of poor accuracy. Detailed procedures can be accurate, but may be labor intensive and perhaps more appropriate for academic studies. Evaluation procedures are complicated by any undulation in the soil-surface topography.

Irrigation Parameter Estimation

Infiltration. Of the procedures available in the literature for estimating infiltration parameters, the simplest is the use of ring infiltrometers. Merriam and Keller (1978) suggest, however, that the infiltration formula constants resulting from ring data be adjusted to provide a volume balance for an observed irrigation. They used a power-law infiltration equation, often referred to as the Kostiakov equation, in which the cumulative infiltrated depth, z, is found from:

$$z = k\tau^{a} \tag{1}$$

Here, τ is the infiltration time, and k and *a* are empirical constants.

Clemmens (1981) found that, when these ring measurements are buffered with the field irrigation water, the procedure appears consistent and reliable for some soils but gives less reliable results for others. Reliability, or consistency, was judged by how similar were the functions fitted to the data for cumulative depth and for infiltration rate, and how much adjustment was needed to provide a volume balance. One reason for disagreement was that some soils reach a final infiltration rate during the irrigation; whereas, equation 1 predicts a continual decrease in infiltration rate. One way (Kostiakov-Lewis formulation) to account for this condition is to add a term to equation 1 that has a constant infiltration rate (i.e., a term, $b\tau$, in which b is the final infiltration rate) achieved after passage of a long period of time, when the contribution of the first term to the infiltration rate becomes negligible. In a more direct approach, Clemmens independently reintroduced (1981) a forgotten *branched* infiltration function devised by Kostiakov (1932) that could be easily fit to the ring data, specifically:

$$\begin{aligned} z &= k\tau^{a} && \text{for } \tau \le \tau_B \\ z &= k\tau_B{}^{a} + b(\tau - \tau_B) && \text{for } \tau > \tau_B \end{aligned} \tag{2}$$

The two branches of this function match infiltrated depth and infiltration rate at time τ_B. They can also be represented by two straight lines on a logarithmic plot of infiltration rate versus time, intersecting at τ_B. In contrast to the Kostiakov-Lewis formulation, a final infiltration rate in the Kostiakov branch function is achieved relatively quickly.

The NRCS (USDA, 1974) proposed a function slightly different from equation 1, which adds a constant term, c, to the right-hand side, i.e.:

$$z = c + k\,\tau^{a} \tag{3}$$

Although the original intent was for a small value of c (a universal constant) introduced only for the purpose of empirical curve fitting, such an equation is particularly useful for characterizing physical phenomena in cracking clay soils, or freshly tilled soils. In these cases, a substantial amount of water infiltrates very rapidly. Then, after the cracks close or the soil consolidates, infiltration proceeds as in other soils (i.e., those characterized by functions without the constant term). Adding this constant to the branch function gives:

$$\begin{aligned} z &= c + k\tau^{a} && \tau \le \tau_B \\ z &= c_B + b\tau && \tau > \tau_B \end{aligned} \tag{4}$$

in which z is the volume infiltrated per unit area of infiltrating surface (i.e., a *depth*), and c, k, a, and b are constants (expressed, for example, in mm, mm/h^a, dimensionless, and mm/h, respectively). At the inundation time τ_B, the infiltration depth z_B and rate $[(dz)/(d\tau)]_B$ given by the two branches are identical. Thus, with c, k, a, and b given, τ_B and c_B follow (see eq. 5, fig. 1).

$$\tau_B = \left(\frac{b}{ak}\right)^{\frac{1}{a-1}} \qquad c_B = c + k\tau_B^a - b\tau_B \tag{5}$$

The constant c_B is simply the intercept of the basic infiltration-rate straight line at $\tau = 0$, a convenience for calculation, as opposed to a formulation based on the infiltration depth at the branch point, $z_B = c + k\tau_B{}^a$.

With ring infiltration data, it is difficult to accurately determine c, since a substantial amount of water may infiltrate prior to the initial water level reading inside the ring. This is particularly a problem for cracking clay soils. Thus, for evaluation of the cracking-clay soils in the Nile Delta, other methods were explored.

Numerous articles have been written over the past decade on estimating infiltration from measurements of water advance. These procedures assume the form of the infiltration function and generally rely on a mathematical model of flow. However, since one of our objectives is to verify such a mathematical model, these kinds of procedures are not appropriate for this study.

More appropriate here are methods for determining infiltration based on a volume balance. These methods compute the subsurface infiltrated volume as the difference between the inflow volume and the volume above the soil surface. By observing the volume infiltrated over time, the infiltration function can be estimated. The various methods differ in how the surface volume is determined and how the subsurface volume is related to the infiltration function. Clemmens (1982) provides a method for estimating infiltration from measured water depths in border strips. This method fits a function through computed average infiltrated depths and times. Scaloppi et al. (1 995) present a similar method for furrows; however, they fit the volume infiltrated over time. A less rigorous method, which

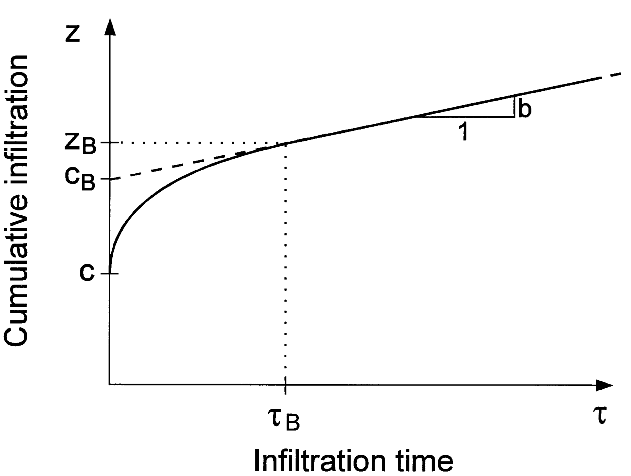

Figure 1–Kostiakov infiltration branch function.

requires only a depth measurement at the head end of the field, is given in ASAE Standards (1993).

Roughness. Surface irrigation models have traditionally used the Manning roughness equation to estimate flow resistance, defined by the so-called friction slope. This is the ratio of the drag of inundated vegetation and wetted boundaries on the flow within the field, per unit length, to the weight of the surface stream, also per unit length. In the Manning equation, the friction slope S_f is related to the discharge Q and flow depth and geometry by:

$$S_f = \frac{Q^2\left(\frac{n}{c_u}\right)^2}{A^2 R^{4/3}} \tag{6}$$

in which A is cross-sectional area of flow, R is hydraulic radius (cross-sectional area of flow divided by wetted perimeter), n is the Manning n ($m^{1/6}$), and c_u is a units coefficient (1.0 $m^{1/2}$/s in SI units, 1.486 $ft^{1/3}m^{1/6}$/s in English units. The mixed length units in the English system stem from the convention of using the same numerical value of n in both English and metric SI systems). Standard, tabulated values of roughness are often used for design (e.g., USDA 1974). Such estimates are based on experience with different crops and soils within the U.S. Additional studies were warranted for Egyptian conditions, since resistance is influenced by planting densities and other cultural practices, typically different from U.S. conditions. In addition to standard tables, three methods are available for estimating Manning n for specific circumstances.

The first method is to provide a constant flow into a furrow or border-strip. After some period of time, infiltration at the head end of the field decreases to a small rate. If the field has a sufficient slope, then the flow depth will build until it reaches a nearly constant value, i.e., normal depth. In this case, the friction slope end bottom slope are approximately equal. With the cross-sectional shape known, measurement of field slope, flow, and water depth, leaves n as the only unknown in equation 6. Unfortunately, field slopes in the Nile Delta are very small, and normal depth is not reached during the irrigation, making this method impractical.

The second method is to use a mathematical model of water advance and determine the Manning n value for which the computed advance best fits the observed advance (e.g., Katopodes et al., 1990). However, since we are also trying to verify such models, this method, too, is not appropriate (at least at this stage).

The third method is to measure field water depths and to compute Manning n from measured water surface gradients, flow rates, and depths from equation 6 (see, for example, Atchison, 1973). For the conditions encountered in Egypt, this was the preferred alternative, even though it is the most difficult to carry out, because the water-surface gradients are hard to measure accurately.

Other Parameters. Standard devices are available for measuring inflow and outflow rates and volumes. Long-throated measuring flumes are preferred for open channel flow measurements (Bos et al., 1984). Field elevation can be measured with standard surveying instruments, although errors on the order of ± 3 mm are likely. Water depths can be measured with pressure-transducers and bubblers (e.g., Dedrick and Clemmens, 1988) or by manual observation of staff gauges.

Irrigation Simulation Models

The first practical surface irrigation simulation model was developed through a cooperative agreement between the U.S. Water Conservation Laboratory and the University of California at Davis (Strelkoff and Katopodes, 1977). The model was based on numerical solution of the continuity and momentum equations, the latter of which was simplified by ignoring the inertial terms. The first independent field verifications of this so-called *zero-inertia* model were published soon after (e.g., Clemmens, 1979). Since then, this basic model has been used for numerous research studies and for education (see, e.g., Walker and Skogerboe, 1987); however, such modeling is not in common use outside the academic community. The original zero-inertia model evolved into the current SRFR program, discussed below.

Finally, while the academic community understands that such models can accurately represent a surface irrigation, the model user is still faced with providing reasonable input data, which requires appropriate formulas along with their empirical constants to describe infiltration and roughness. We demonstrate herein that if the parameters are accurately estimated, then the zero-inertia model can reasonably predict water advance and recession.

The zero-inertia model is described here in abbreviated form for the convenience of the reader. It can be found in numerous references. The model is based on solution of the continuity and momentum equations, the latter with (negligibly small) acceleration terms deleted:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} + \frac{\partial A_z}{\partial t} = 0 \quad (7)$$

$$\frac{\partial y}{\partial x} = S_0 - S_f \quad (8)$$

in which y is flow depth, x is distance, t is irrigation time, A_z is infiltrated volume per unit length, S_0 is bed slope, and S_f is friction slope. In the current application, the Manning equation is used to define S_f from equation 6. Specification of boundary conditions for solving the above equations can be found in Walker and Skogerboe (1987).

The results of an irrigation simulation for a flat-planted basin or border strip, or furrow depend upon the input:

Geometric Parameters:

L = field length

W = set width (or, with a furrow, specified size, shape, and spacing)

S_0 = bottom slope

End conditions (open end, blocked end, etc.)

Soil and Crop Conditions:

Manning n

Modified Kostiakov or Kostiakov Branch values of k, *a*, b, and c

Operating Conditions (Inflow Hydrograph):

Flow rate Q_0 (or, in borders and basins, unit flow rate $q_0 = Q_0/W$)

Application or cutoff time, t_{co}

The results of the simulation are (a) the runoff hydrograph and volume, (b) the distribution of infiltrated water across the field, and (c) performance parameters based on these and a stated (uniform) infiltration requirement.

Field Experiments

Data Collection

A series of field experiments was conducted on wheat for the 1993-1994 and 1994-1995 seasons, and on cotton during 1994. Details are described in El-Haddad et al. (1999). These experiments were used to test the effects of various cultural practices on advance and irrigation performance. In part, these effects were related to differences in infiltration and roughness parameters. In this article, we describe the procedures used to determine parameter values.

For the wheat studies, typically two basins or border strips were irrigated with a single stream. Long-throated flumes were installed at the entrance to the field and within the head-ditch between the two basins being irrigated. The second flume gave the flow rate to the second basin, while the difference between the two flumes gave the flow to the first basin. Water-depth measurements were taken from staff gauges placed along one edge of the basin, spaced about 30 m apart, starting from the head end. These gauges consisted of 30-cm wooden scales wired to lengths of reinforcing steel; the steel was driven into the soil, so that the bottoms of the scales rested at or near the soil surface. The field dimensions were measured with a tape, while field elevations and the elevations of the tops of the scales were measured with a standard surveyor's level.

For the cotton studies, individual 15-m-wide basins were prepared for each treatment; the number of furrows in each basin varied with the furrow spacing. During irrigations for which parameter estimates were desired, flow was divided between two groups of four furrows for each treatment, with a flume at the head of each group. Two furrows within the group were instrumented with staff gauges to measure water depth, approximately every 30 m. The furrow spacing and length were measured for each basin. A representative furrow cross section was obtained by measuring a transverse profile of soil depth below a horizontal bar placed across the furrow. A surveyor's level was used to measure field and staff-gauge elevations in the furrow bottom at each station (see fig. 2).

Data Analysis—The EVALUE Program

In order to facilitate the analysis of the data collected, a computer program, EVALUE, was written. EVALUE is designed to read a file into which the raw data from the experiments has been entered, then allow the user interactively to select appropriate numerical values for the infiltration and roughness parameters, and, finally, record these automatically in an output file for subsequent entry into a simulation or design program.

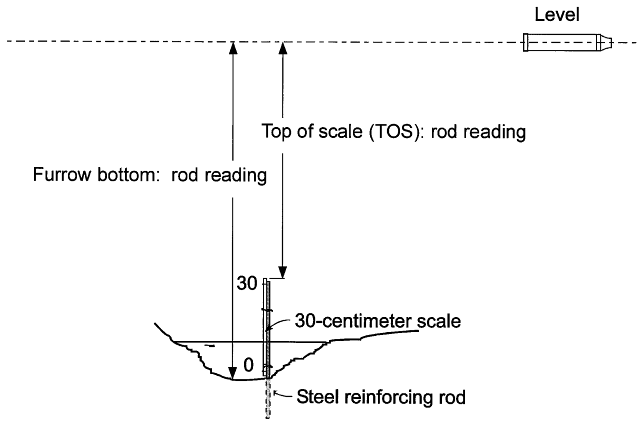

Figure 2–Level survey data.

EVALUE is a time-saving convenience for an irrigation engineer processing raw data gathered in the field for an evaluation of infiltration and roughness conditions during an irrigation. It is ***not*** an ***expert system*** providing quick and easy interpretation of the field data. It is designed for use by an engineer trained in the elements of surface irrigation. Judgement is required at several points in the analysis; the less precise the field data, the greater the need to exercise good judgement. The user will have to decide judiciously how to deal with anomalies, e.g., what is the magnitude of the error likely in the field data, what field data suggests blunders (for example, reading stadia hairs in place of the middle cross hair during a level survey, unnoticed leakage around flow-measurement flumes, breakage of berms, etc.).

For these reasons, curve fitting of field data with theoretical expressions is performed manually, interactively *with* the computer, rather than automatically, *by* the computer. This gives the user the responsibility for the resulting evaluations, rather than relying upon a single numerical *"answer"* given by one or another automatic curve-fitting algorithm.

A basic assumption in the analysis is that the infiltration characteristics are uniform over the length of a test furrow or basin. Implied in the analysis, though not essential in principle, is the assumption that the infiltration in the neighboring two uninstrumented furrows is the same, on average, as the two instrumented furrows. It is also assumed that the measured inflow is distributed equally to all furrows sharing the common source. To the extent that the infiltration characteristics of the soil actually do vary over the length of the border or furrow, and from furrow to furrow, and that the inflows to neighboring furrows are not identical, the resultant parameter values determined could well be in significant error.

A working assumption, furthermore, is that all of the cross-sections of test furrows in the irrigation are represented by the single transverse profile of soil-surface depth (fig. 3). Any anomalies introduced into the tests by nonprismatic furrows are reflected in irregularities in the field data being fitted by theoretical expressions.

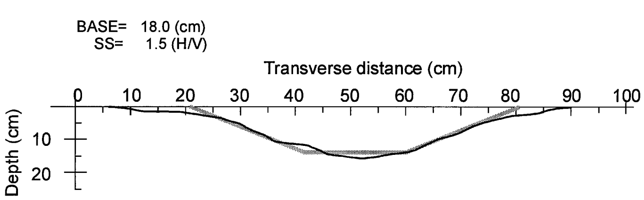

Figure 3–Fit of trapezoid to measured furrow cross-section data.

CONVERSION OF RAW DATA TO USABLE FORM

Because of the large number of workers involved in manual data gathering and other technical considerations, it was not possible to enter measured data automatically into the data-input file. Consequently, transcription errors could have occurred as the penciled notes of the data collectors were manually entered into the computer. However, in order to avoid human error in on-site calculation, the data-input format for EVALUE allows entry of field-measured values, as read, directly into the data file.

EVALUE provides considerable flexibility in preparation of the data files, for example, the number of data entries, interpolation of blank lines for readability of the file, choice of columns in which to enter the data, entry of comments helpful in interpreting anomalies, etc. However, as noted in the foregoing, EVALUE allows direct (manual) entry of raw data, just as read by the technicians. With different kinds of tests requiring different kinds of data, EVALUE requires entry of prescribed character strings heading up each group of data. These tell the program what follows, units, etc. The different types of tests are associated with specific named formats.

For example, in MOSHTOHOR FURROW format, the input file provides the number of furrows sharing the measured supply, and the number of instrumented test furrows. Level-survey data (fig. 2) follows, with station locations, rod readings to the bottom of each furrow, end to the top of each 30-cm wooden scale comprising the staff gauge for visual measurements of water-surface elevations.

The furrow geometry is completed with the measurements for the typical transverse elevation profile of the furrow. Figure 3 shows EVALUE's screen plot of the measured transverse profile, the first screen of data to be viewed by an EVALUE user (for the reader's benefit, pertinent numerical scales have been added). The plot of transverse measurements is complemented by a user-fitted trapezoid, to be used in subsequent calculations of water volumes in the furrow. The location of the trapezoid relative to the measured profile and its base and side slopes are adjusted by the user through the arrow keys and prescribed letter keys to obtain the best fit, interactively. The user can select a power-law cross section or a trapezoid.

The inflow hydrograph—a table of time versus flume reading—is read next. For the Moshtohor tests, small fiber glass RBC flumes reading directly in liters per second (L/s) (Bos et al., 1984) were brought in from the U.S. Larger flumes were constructed on site, of wood or concrete, according to specifications provided by the computer flume-design program, FLUME (Clemmens et al., 1993); flows in these flumes were evaluated by reading a centimeter scale affixed to the wall of the approach section in a prescribed location. The MOSHTOHOR format provided a framework for specification of what size and type of flume was used, and EVALUE applied any necessary calibration formulas to the measurements.

Technicians stationed along the instrumented furrows, having synchronized stop watches when the inflow was initiated, noted the time and elevation of the water surface on the aforementioned wooden scales. This information, entered directly as measured into the data file was reduced by EVALUE together with the survey data to yield depth and water-surface-elevation hydrographs and profiles. In EVALUE, the depth data together with the fitted trapezoid were used to calculate volumes of water in the furrows as a function of time, while water-surface profiles were used to estimate water-surface slope for calculated furrow roughness. Important byproducts of the depth hydrographs were advance and recession times for each station. When measured depth hydrographs did not extend to the time of water recession, recession time was estimated by noting the depth of water at the last measured time and assuming that the remaining surface depth infiltrates in place.

Adjustment of Level-rod Readings

Figures 3 through 8 illustrate computer screens displayed in the course of an interactive session (for greater clarity, axis and curve labels as well as numerical scales have been added, compared to the information actually shown on the screen). Following user selection of a fitted cross section, as in figure 3, the measured upstream inflow hydrograph and water-surface hydrographs at all stations are displayed on the EVALUE screen shown as figure 4. Additional text shown on the screen refers to the interactive adjustments available to the EVALUE user (for example, to rod readings, TOS, to the top of the depth scales of fig. 2, or the exponent in a power-law fit to the profiles of fig. 6).

The user can toggle between displays of the measured hydrographs and corresponding water-surface profiles (fig. 5) calculated from the depth hydrographs.

These displays may indicate errors in survey data and water-level records. For example, water surfaces *must* slope downward in the direction of flow, and become level when the stream is ponded in a basin. Any evident departures from these norms must be viewed as errors, possibly in the level- survey data, or in a post-measurement shift in the vertical position of a staff-gauge scale. Judicious on-line adjustment of rod readings can be made at this point from the keyboard, with a combination of letter and arrow keys. Any selected corrections are

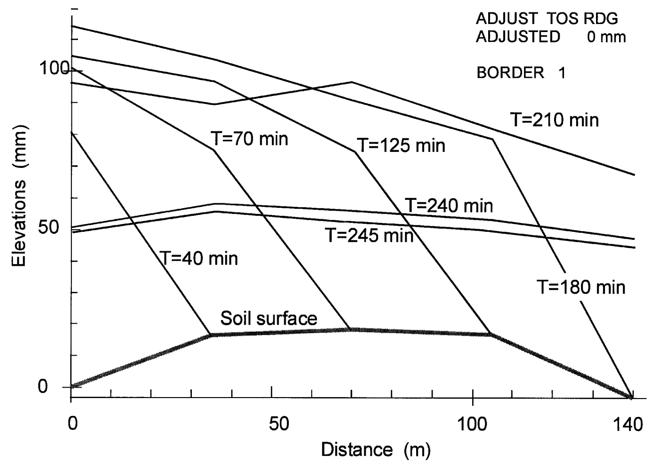

Figure 5–Measured field-surface elevations and water-surface profiles.

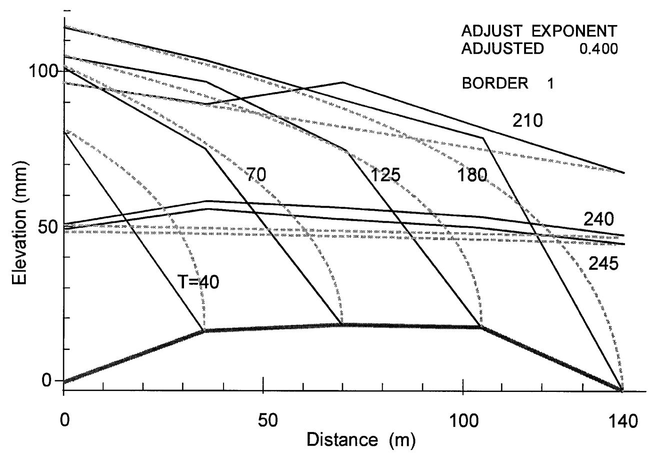

Figure 6–Smooth, fitted water-surface profiles (for slope estimation only).

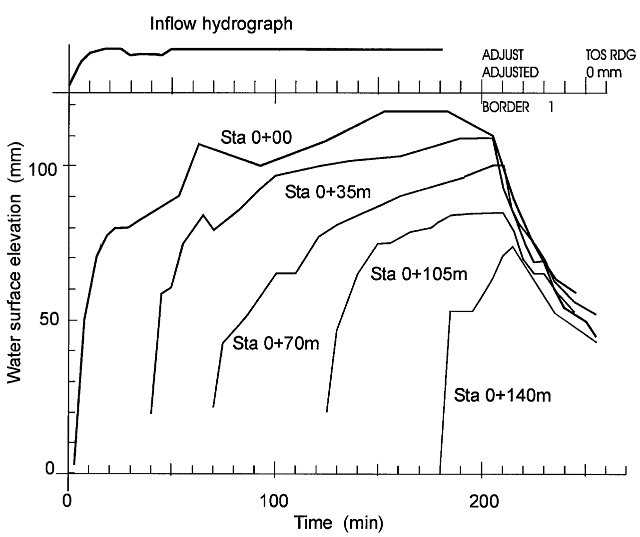

Figure 4–Measured inflow and water-surface hydrographs.

appended to the data file, without altering the initially entered data, so that subsequent applications of EVALUE to a data set reflect previously selected corrections.

For the purpose, only, of estimating water-surface slope in roughness calculations, smooth power-law curves (shown dotted in fig. 6) are fit to the measured profiles. If they wish, users can use the keyboard to adjust EVALUE's selection of the parameters of those fitted curves.

When the hydrographs/profiles have been accepted by the user, the next EVALUE screen displays the measured advance as a function of time, along with a power-law advance equation to fit to the data. The coefficient and exponent can be changed from the keyboard, so that the user can find the equation that best matches the field data (screen text reminds the user which keys to press to adjust the displayed coefficient and exponent). The fitted power law is not used in any subsequent EVALUE calculations, and the parameters of the expression are merely entered in the output file.

Evaluation of Infiltration

Next, superpositions of measured and calculated accumulated infiltrated volumes as functions of time are

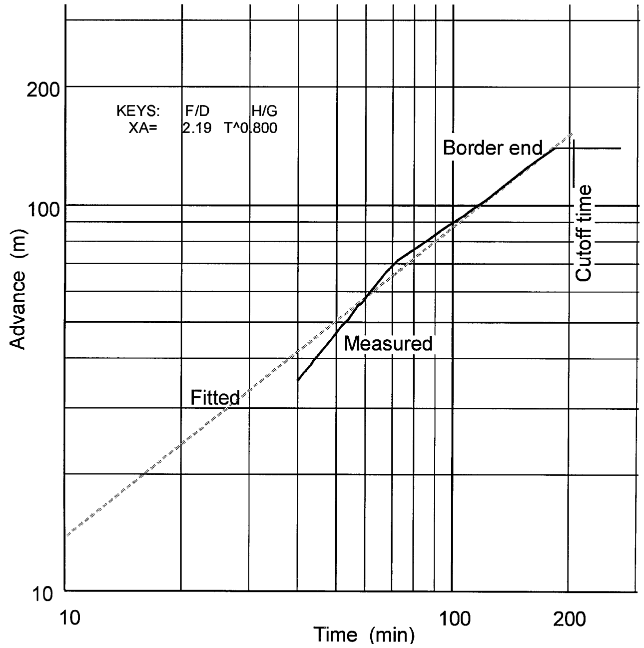

Figure 7–Measured and fitted advance curves.

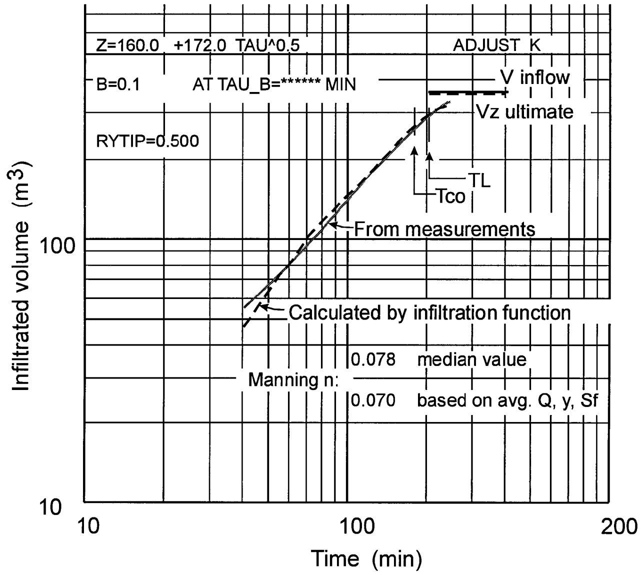

Figure 8–Measured and calculated growth of total infiltrated volume.

shown, for on-line estimation of parameters in the infiltration and roughness formulas.

Measured Infiltrated Volume. Fundamentally, infiltration parameters are found by matching the measured growth of infiltrated volume during the irrigation, to growth calculated on the basis of measured advance and the selected values of the infiltration parameters. The measured growth of infiltrated volume for a border or furrow is derived from measured values of inflow volume $V_Q(t)$ and volume of surface water, $V_y(t)$:

$$V_z(t_i) = V_Q(t_i) - V_y(t_i) \tag{9}$$

The subscript i refers to the index of a time level; surface-water profiles, and consequent volumes of water in the border or furrow, are calculated each time the stream reaches a station. Once the stream reaches field end, profiles are calculated every 30 min in borders, and every 60 min in furrows. Volumes under the depth profiles are computed with trapezoidal-rule numerical integration applied to the cross-sectional areas calculated from the fitted furrow cross section and measured depths at the successive stations.

The trapezoidal rule is modified in the forward-most segment of the flow profile during advance, by allowing the user to specify a power-law shape, through specification of a *shape factor* R_y. This weights the first measured area upstream from the zero area at the very front of the wave by more than 1/2 (1/2 being the value prescribed by the trapezoidal rule and corresponding to a triangular shape for the front of the profile). This would correspond to a surface-water profile convex upward near the front, typical for robust advance (after cutoff, if the stream has not yet reached the end of the field, the stream profile as it slows its advance may turn concave upward, corresponding to a power law that leads to a shape factor less than 1/2). The magnitude of this shape factor can, at small times, significantly affect the calculated surface volume temporarily stored within the border or furrow. Allowing user control over its value can facilitate the fitting of infiltration parameters to the early portions of the irrigation event. Strictly speaking, the power-law fit to each individual water-surface profile (as in fig. 6, and subsequently used for Manning n calculations), implies a value of the wave-front shape factor, but in EVALUE, the user can enter R_y—used for determining infiltration—independently. On the other hand, the two should at least approximately agree.

The volume of inflow is obtained by applying the trapezoidal rule to the volumetric rates of inflow and associated time values in the measured inflow hydrograph. In the data file, cutoff is assumed to occur immediately after the last discharge/time entry. The total volume of inflow is divided evenly among the total number of furrows sharing that inflow, a procedure that may not be justifiable, especially in a poorly graded field.

In the screen plot, current user-selected infiltration parameters are displayed, as well as an indication of which parameter (e.g., k, in fig. 8) is subject to adjustment with the arrow keys. In the figure, the stars shown for τ_B simply indicate that the value corresponding to the selected value for b (0.1 mm/h) is too great to fit the programmed format. Vertical tick marks are placed at the time of cutoff, t_{co}, and at the advance time of the stream to field end, t_L.

Note that if advance is not completed to the end of the field in any of the test furrows, the procedure is carried out for whatever stations have measured water depths. The profiles are arbitrarily brought to zero depth at the station following the one for which depth data exists. This can overestimate the surface storage, under the profiles. In calculating that volume, however, the user-selected tip shape factor can provide some control over the influence of this arbitrary maximum advance distance.

Calculated Infiltrated Volumes Based on Kostiakov/Clemmens Parameters. The basic approach to finding these infiltration parameters from an instrumented field irrigation is to match the growth with time of total volume infiltrated, derived as above, with calculations based on measured inundation times and estimated parameters in a selected infiltration formula.

The modified Kostiakov branch-function formula (eqs. 4) has been selected for use in EVALUE, because it exhibits a theoretically correct behavior, with large infiltration rates initially, reducing to a constant, final infiltration rate, and because it was possible, by appropriate selection of the constants therein, to fit the Egyptian soils encountered.

The calculated growth of infiltration volume is determined by estimating the growth of infiltrated volume per unit field area $z(t_i)$, for some choice of parameters c, k, a, and b, in equations 4 and inundation times τ at each station measured from the time of stream arrival there. This is then multiplied by the border width or furrow spacing W to obtain the volume infiltrated per unit length of furrow, $A_z(x_k,t_i)$, and then integrated along the length. Here x_k is the location of the kth station along the furrow or basin, and t_i is the *ith* time level in the procedure. In view of the extensive cracks in the soil, water is distributed laterally from a furrow without much regard for the macro-scale wetted perimeter; thus, any influence upon infiltration of variations in that wetted perimeter with stream depth were ignored.

Numerical integration over increments of distance along the furrow yields increments of infiltrated volume in accord with the formula:

$$\delta V_{z_{k,i}} = \left[\phi A_{z_{k-1,i}} + (1-\phi) A_{z_{k,i}}\right] \times (x_k - x_{k-1}) \quad (10)$$

in which the shape factor ϕ is based on an assumed power-law variation of A_z with distance back from the front of the stream (in the trapezoidal rule, ϕ = 1/2). Summing the increments yields V_{z_i}.

Both calculations of $V_z(t)$, the measured and the calculated, are graphed on the screen, while the user seeks the best possible match by selecting appropriate values of the four infiltration parameters from the keyboard. On the grounds that neighboring furrows probably exhibit similar soil-infiltration characteristics, curves for both test furrows are plotted simultaneously so that the best fit of both can be achieved by manipulating the parameter values. Differences in the results for the two furrows can be due to unequal division of inflow as well as differences in geometry and infiltration.

An additional guide to the choice of infiltration-parameter values is provided by matching the total, post irrigation calculated infiltration volume to the total volume of inflow. The former is estimated by the aforementioned technique for calculating A_z at each of the stations up to the maximum time read in each hydrograph. Any surface-water cross-sectional area remaining at this time (because the recession was not observed) is simply added, on the assumption that the remaining water will infiltrate in place.

Selection of Parameter Values. In general, in selecting the infiltration parameters, matching of the accumulated-volume curves was considered more important at moderate to large times, than at small times. Furthermore, it was found that, with four infiltration parameters to select, the ultimate choice was influenced to a considerable degree by subjectivity. Equally good fits could be obtained with widely disparate values of the parameters, large values in one parameter corresponding to small values of another. This only shows that over the time range of the irrigation, one choice is as good as another. However, selections based on blind fitting of the curves without regard for physical realities could result in problems with subsequent simulations. For example, very small values of the Kostiakov exponent, for example, a = 0. 01, could be found to yield a satisfactory fit. On the other hand, selection of such an unrealistic value for a introduces an extreme degree of nonlinearity in the governing equations, which simulation programs like SRFR attempt to solve numerically. Without impractically small time and distance steps and very careful selection of numerical-solution parameters, the simulations fail. Yet the physical significance of a very small fitted value of a is merely that a substantial volume of water infiltrates initially, with little infiltration subsequently (unless provided in the b term). A more reasonable approach to this physical circumstance is to provide for that initial volume with the constant term c (in eqs. 4, 5), and allow a to have normal values. It was found that all of the Egyptian soils data could be fitted reasonably well with the theoretically derivable value of a = 0.5 (Philip, 1957), and a commensurate value of k, as well as b and c, to make the fit. In some cases, $z = c + b\tau$ could provide a reasonable fit, expressing the physical circumstances well. However, in each case it was possible to use just the simple two-parameter formula, $z = c + k\tau^{1/2}$. These soils did not appear to reach a final, constant infiltration rate within the time of our measurements.

Evaluation of Hydraulic Roughness

As noted in equation 6, hydraulic roughness can be defined in terms of the friction slope S_f. At the very low velocities typical of surface irrigation, this term reduces simply to the slope of the water surface, directly derivable from the profiles already calculated. The hydraulic radius can be found in terms of the known depth and simplified cross-sectional shape. This leaves only the local discharge $Q_{k,i}$ to be found.

The growth of surface and subsurface volumes (per unit length) is related to the decrease in discharge with distance along the stream by the equation of continuity (eq. 7), or, following numerical integration of equation 7, over the distance between stations and the time step between successive profiles:

$$Q_{k,i} = Q_{k-1,i} + \frac{(1-\theta)}{\theta} Q_{k-1,i-1} - \frac{(1-\theta)}{\theta} Q_{k,i-1} - \frac{\delta\delta V_y + \delta\delta V_z}{\Delta t \theta} \quad (11)$$

The increments $\delta\delta$ in the surface and subsurface volumes are illustrated in figure 9 for k = 3, i = 4, and are found by subtraction of the volumes at time i – 1 from those at i. The term θ is a weighting factor for the numerical integration of equation 7 in time. Its value is θ = 0.5, except for the initial rise of Q at a station immediately after the stream arrives there. For that time increment, θ is set to 0.7.

Values of the Manning n are calculated by EVALUE at the stations and at the times for which profiles have been

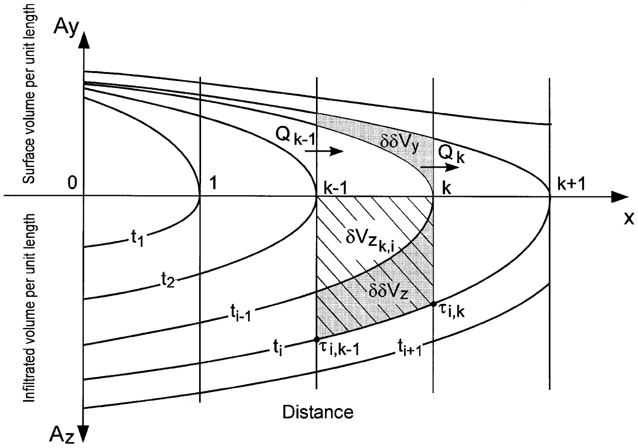

Figure 9–Calculation of infiltrated volume.

calculated. Measured depths (areas, hydraulic radius), water-surface slopes (S_f) from the fitted smooth profiles, and discharges from equation 11 (see fig. 9) enter into the computations of equation 6 for n at successive x_k and t_i. The user can judge the precision of the measurements by noting the variation in calculated n values. Large variations unexplained by physical conditions are evidence of poor data. For selection of a *representative* value of n for the irrigation, EVALUE computes the average and the median values from amongst the various k and i. The user can choose one of these, or take a numerical average of the two, for entry into simulation or design programs.

EXAMPLES

Figure 10 compares the results of a simulation for a border strip (WLlR2-30) with field data collected in the 1994-1995 growing season (see El-Haddad et al., 1999, for details). The simulation program SRFR was provided with infiltration and roughness parameters estimated with EVALUE (figs. 4-8), and bottom geometry and inflow hydrograph from field-measured data. In this greatly cracking soil, the selected value for the Kostiakov k was 172 mm/h^a, the constant term c = 160 mm, and the exponent a = 0.5. The Manning n selected was 0.075. Superimposed on the SRFR simulated advance, recession,

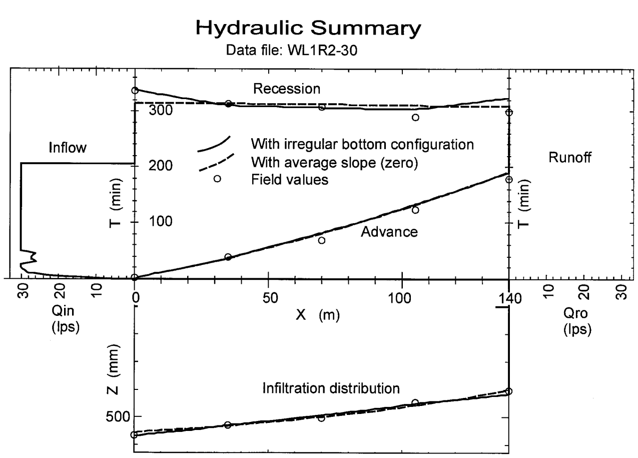

Figure 10–Comparison of results of simulation and field data in a border strip.

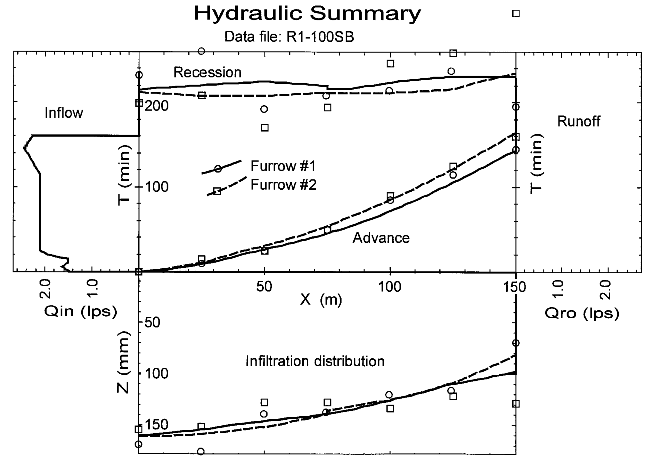

Figure 11–Comparison of results of simulation and field data in an adjacent pair of furrows. Continuous curves = simulations; squares and circles = data from measurements.

and infiltration distribution curves shown in figure 10 are the values generated from the field data. Infiltration and recession measurements are adjusted for a balance between infiltrated and inflow volumes, to the extent this was not accounted for in the course of the interactive session. At least for this example, the volumes were not influenced significantly by variations in bottom elevation. The agreement is clear.

An evaluation and simulation for a pair of furrows (R1-100S) from the 1994 cotton season is shown in figure 11. The match is not as good as in figure 10, reflecting the problems encountered with data from this group of field tests. But even in this case, qualitative agreement is good.

Additional applications of the procedures are documented in the companion articles, Clemmens et al. (1999) and El-Haddad et al. (1999).

CONCLUSIONS

With due care in collecting and entering field data, infiltration and roughness parameters suitable for entry into simulation models can be found with the assistance of the EVALUE software. The closeness of match between simulation and observation reflects not only the care with which data was taken, but also the degree to which assumptions regarding field uniformity are justified (for example, identical inflows to neighboring furrows, or spatially invariant infiltration and roughness). Though further work is needed to assess the likely degree of error incurred by making these assumptions, it is clear that the SRFR simulation program is capable of modeling surface irrigations under Egyptian conditions.

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Symbols

a	exponent in Kostiakov power-law infiltration formula
$A(x,t)$	cross-sectional area of irrigation stream (volume per unit length)
$A_z(x,t)$	volume infiltrated per unit length
b	basic (final; large-time) infiltration rate
c	volume infiltrated, per unit area, as soon as water is applied
c_u	units coefficient in Manning formula allowing same numerical value of n to be used with different systems of units
k	Kostiakov power-law coefficient
L	length of run
n	Manning coefficient
$Q(x,t)$	volumetric flow rate
Q_0	inflow rate
q	flow rate per unit width
R	hydraulic radius: *cross-sectional area of flow/wetted perimeter*
S_0	bottom slope
S_f	friction slope: *flow resistance per unit length/stream weight per unit length*
t	time
t_{co}	time at which inflow is cut off
V_Q	volume of inflow
V_y	volume in irrigation stream
V_z	volume infiltrated
W	furrow spacing, or width of border or basin
x	distance along the length of run
y	flow depth
z	depth of infiltration: volume per unit area
δ	increment in volume over a distance increment *at* a specific time
$\delta\delta$	increment in volume over a distance increment *and* a time increment
θ	weighting factor relating average value of an integrand changing with time to values at beginning and end of time step
τ	infiltration time
τ_B	time at which power-law infiltration rate matches final rate (see fig. 1)
ϕ	weighting factor relating average volume per unit length infiltrated between cross-sections to volume per unit length at each of the bounding sections